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Analysis of Fatal Accidents Involving Front-End Loaders at Metal and Nonmetal Mines, 1972-74

UNITED STATES DEPARTMENT OF THE INTERIOR
Mining Enforcement and Safety Administration
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Analysis of Fatal Accidents Involving Front-End Loaders at Metal and Nonmetal Mines, 1972-74

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ANALYSIS OF FATAL ACCIDENTS INVOLVING FRONT-END LOADERS AT METAL AND NONMETAL MINES, 1972-74

by

R. H. Oitto[1] and R. R. McLellan[1]

ABSTRACT

A critical accident trend has been identified which involves the front-end loader. The rubber-tired type of front-end loader that is widely used in metal and nonmetal mining is particularly involved in this trend. Eighteen fatal accidents occurred in 1972, 20 fatal accidents occurred in 1973, and 15 occurred in 1974. The sand and gravel industry accounted for 30 fatalities, or 56 percent of the total for the 36-month period of investigation. Analysis of the accident reports indicates that 74 percent of the total injuries probably could have been avoided had adequate protection been provided to the loader operator in the form of a roll-over protective structure (ROPS) and seat belts. More than half of the fatal accidents occurred as the result of backing off roadways or stockpiles and losing control of the loader while traveling downgrade. These accidents resulted in 31 fatalties, or 58 percent of the total for 1972-74. Usually, the loader overturned throwing the operator into the path of the machine. Operator error and lack of training are the primary factors in causing loader accidents. The analysis indicates that the installation of roll-over protection on the machines and the providing of adequate training for loader operators will contribute substantially towards a reduction of the accident rate.

INTRODUCTION

This report provides a preliminary analysis of 53 fatal accidents caused by front-end loaders at metal and nonmetal mines during 1972-74. This portion of the study is limited to the analysis of accident data and information obtained from Health and Safety Reports of Fatalities prepared by Mining Enforcement and Safety Administration (MESA) inspectors representing the Metal and Nonmetal Mine Health and Safety Districts in which the accidents occurred.

Ten factors related to front-end loader fatalities that were obtainable from the MESA fatality reports are analyzed. Those factors are: (1) cause of accident, (2) activity of loader, (3) presence or absence of roll-over protection and seat belts, (4) probability that the fatality could have been prevented with roll-over protection and seat belts, (5) experience of operator

[1]Mining engineer.

at running loaders, (6) experience of loader operator at mine, (7) occupation of operator, (8) mine product, (9) time of day that the fatality occurred, and (10) age of operator of loader.

There are other factors which may contribute to front-end loader accidents, but they are beyond the scope of this report because of the limited data available from the fatality reports. Some of those factors are (1) lack of standardization of controls on loaders, (2) loader center of gravity, and (3) design and construction of haul roads, loading ramps, and access roads. Sufficient information was not available from the reports to determine which manufacturers and models of loaders and mechanical deficiencies contribute to the accidents.

The number of fatalities from front-end loaders for 1974 is subject to change. Anyone injured by a front-end loader in 1974 who dies during 1975 as a result of that injury will be charged to 1974.

ANALYSIS

The following tables analyze 10 factors, all related to 53 fatalities associated with the operation of front-end loaders at metal and nonmetal mines during 1972-74.

Table 1 indicates that there are three principal causes that account for 39 of the fatalities, or 73 percent of the total; these being overturns as a result of backing off a stockpile, loss of control downgrade, and striking persons who were not operating the loaders.

TABLE 1. - Front-end loader fatalities, by cause

Cause	1972 fatals	1973 fatals	1974 fatals	Total	Percent
Operator backed loader off road or stockpile, causing it to overturn........	5	8	3	16	30
Operator lost control of loader downgrade, causing it to overturn..................	7	4	4	15	28
Operator struck nearby pedestrian or worker with loader......................	5	0	3	8	15
Shoulder caved, loader overturned........	1	1	2	4	7
Passenger fell off loader, crushed by wheels................................	0	1	2	3	6
Operator backed loader into other equipment..............................	0	2	0	2	4
Bank caved knocking loader over bench.....	0	1	0	1	2
Operator drove loader forward over embankment	0	1	0	1	2
Operator drove loader into pond at night..	0	0	1	1	2
Operator tossed off loader...............	0	1	0	1	2
Operator turned too sharply, caused loader to overturn.....................	0	1	0	1	2
Total.............................	18	20	15	53	100

Table 2 indicates that more than half of the front-end loader fatalities occurred outside the load-dump segment of the mining cycle. Activities other than loading and dumping included such operations as delivering supplies; pulling heavy equipment such as bins, draglines, and railroad cars; bulldozing with the bucket; back-leveling rough surfaces with the bucket; and driving from one work place to another or to or from the repair shop. Because front-end loaders can be used in many ways, they are driven not just on haul roads, but also on access roads and sometimes on trails intended only for dozers having crawlers. They often are driven and used on roads and in work areas neither designed nor constructed for them.

TABLE 2. - Front-end loader fatalities, by activity

In load-dump cycle	1972 fatals	1973 fatals	1974 fatals	Total	Percent
Yes...............	6	11	6	23	43
No................	12	9	9	30	57
Total........	18	20	15	53	100

The 41 front-end loaders in table 3 were involved in roll-over or cab-crushing types of accidents. None of the loaders had roll-over protection or a seat belt. As for the other 12 accidents in table 3, roll-over protective structures (ROPS) and seat belts would not have prevented the deaths. In 8 of those 12 accidents, the victim was a pedestrian or worker near the loader and was crushed. In three accidents, a passenger fell off the loader and was crushed under the wheels. In one accident, the operator drove into a pond at night and drowned.

TABLE 3. - Front-end loader fatalities related to presence or absence of safety devices

Roll-over protection and seat belts	1972 fatals	1973 fatals	1974 fatals	Total	Percent
Not on loader.........................	13	19	9	41	77
On loader.............................	0	0	0	0	0
Not applicable to accident...........	5	1	6	12	23
Total..........................	18	20	15	53	100

Table 4 indicates that out of the total of 53 fatal accidents involving front-end loaders, 29 had a high probability of being prevented by the use of roll-over protective structures (ROPS) and seat belts. In each instance, the operator was crushed as a result of being thrown into the path of the over-turning loader. The slope drops ranged from 1 to 15 feet, involving a relatively short overturn distance.

As listed in the table, 10 additional fatal accidents were of such a nature that the operators might have survived had roll-over protection, including seat belts, been installed on the machines. In most of those accidents, the loader rolled over more than once on slope drops greater than 15 feet. In overturns involving near vertical drops or steep slopes of great length, the value of the safety devices probably are minimal considering the weight of

the machine. In two accidents, the operators could have survived the overturn, but might have drowned in the ponds where the loaders stopped rolling.

TABLE 4. - Probability of prevention of fatal injury with use of roll-over protection and seat belts

Probability	1972 fatals	1973 fatals	1974 fatals	Total	Percent
High	10	12	7	29	55
Moderate	2	6	2	10	19
Low	1	1	0	2	4
Not applicable	5	1	6	12	22
Total	18	20	15	53	100

Two fatalities listed in the table had a very low, if any, chance of being prevented by ROPS. In one accident, the loader went off a 74-foot high face at a quarry. In the other accident, the loader went off an access road and traveled out of control a distance of 568 feet, bouncing and rolling often, before stopping demolished.

The 12 fatal accidents listed as not applicable involved the crushing of 11 workers other than loader operators who, in some manner, were working or walking, or fell into the path of the loader, and one loader operator who drowned.

The distribution in table 5 tends to justify the comments written by several mine inspectors in their fatality reports concerning the lack of operating experience of many of the victims. The operating experience of 11 victims, or 21 percent of the total for 1972-74, apparently was not available to the investigating personnel. Several of the 11 might be expected to fall in the less than 1 year experience category.

TABLE 5. - Operating experience of front-end loader operators involved in fatalities

Years operating experience	1972 fatals	1973 fatals	1974 fatals	Total
<1	2	8	4	14
1 <2	2	1	1	4
2 <3	1	0	0	1
3 <4	0	0	0	0
4 <5	1	2	1	4
>5	3	3	2	8
Unknown[1]	9	6	7	22
Total	18	20	15	53

[1] Includes a total of 11 operator-victims whose experience was not given in the fatality reports and a total of 11 nonoperator victims. Reports of nonoperator fatalities do not give the experience of the operator involved.

The distribution in table 6 parallels that of table 5 with regard to the correlation of the first year of operating experience and the first year of mine experience at the mines where the accidents occurred. Obviously, the

first year of operating a front-end loader is the most critical time for the operator expecially when that year is his first year at a mine.

TABLE 6. - Total experience of loader operator at mine where fatality occurred

Years at mine	1972 fatals	1973 fatals	1974 fatals	Total
<1	2	8	5	15
1 <2	2	2	0	4
2 <3	4	1	1	6
3 <4	1	0	1	2
4 <5	0	2	1	3
>5	4	3	0	7
Unknown[1]	5	4	7	16
Total	18	20	15	53

[1]Includes a total of 5 operator-victims whose experience was not given in the fatality reports and a total of 11 nonoperator victims. Reports of non-operator fatalities do not give the experience of the operator involved.

According to the distribution in table 7, 14 victims of the 42 who were actually operating the machines were not classified as loader operators, thus prompting the question of operator qualification.

TABLE 7. - Front-end loader fatalities, by occupation of operator

Occupation	1972 fatals	1973 fatals	1974 fatals	Total		Percent
Loader operator	9	12	7	28		= 53
Equipment operator[1]	0	3	0	3	14	= 26
Truck driver	0	1	2	3		
Foreman	1	1	0	2		
Maintenance man	1	1	0	2		
Laborer	0	0	1	1		
Scraper operator	1	0	0	1		
Shovel operator	1	0	0	1		
Rotary operator	0	1	0	1		
Unknown[2]	5	1	5	11		= 21
Total	18	20	15	53		100

[1]Operated more than one kind of equipment.

[2]These are accidents in which the operator was not the victim. Only the victim's occupation is given in the MESA fatality reports.

Table 8 indicates that most of the fatalities are associated with the sand and gravel industry, followed by limestone and traprock mining to a lesser extent.

TABLE 8. - Front-end loader fatalities, by mine product

Product	1972 fatals	1973 fatals	1974 fatals	Total	Percent
Sand and gravel........	8	13	9	30	56
Limestone.............	5	1	4	10	19
Traprock..............	1	3	1	5	9
Sandstone.............	1	0	1	2	4
Lead-zinc.............	1	0	0	1	2
Phosphate.............	1	0	0	1	2
Salt..................	1	0	0	1	2
Talc..................	0	1	0	1	2
Clay..................	0	1	0	1	2
Copper................	0	1	0	1	2
Total............	18	20	15	53	100

The distribution in table 9, as might be expected, indicates that most of the fatalities occurred on the day shift; that being the period of greatest loader activity.

TABLE 9. - Front-end loader fatalities, by time of day

Time of day	1972 fatals	1973 fatals	1974 fatals	Total
8-12 a.m.......................	6	6	4	16
12-4 p.m.......................	6	5	6	17
4-8 p.m........................	1	3	3	7
8-12 p.m.......................	2	0	1	3
12-4 a.m.......................	2	2	0	4
4-8 a.m........................	1	4	1	6
Total....................	18	20	15	53

Table 10 presents the distribution of fatalities by age of operator and indicates no trend using data that are not normalized.

TABLE 10. - Front-end loader fatalities, by age of operator

Age of operator	1972 fatals	1973 fatals	1974 fatals	Total
18-20..........................	1	1	0	2
21-25..........................	2	1	1	4
26-30..........................	0	4	1	5
31-35..........................	3	1	0	4
36-40..........................	0	2	1	3
41-45..........................	1	4	3	8
46-50..........................	3	3	1	7
51-55..........................	1	3	1	5
56-60..........................	0	0	1	1
61-65..........................	2	0	1	3
Unknown[1].......................	5	1	5	11
Total....................	18	20	15	53

[1]These are accidents in which the operator was not the victim. Only the victim's age is given in the MESA fatality reports.

CONCLUSIONS

The following conclusions are based upon data and information available from the fatality reports and from qualified MESA personnel:

1. A reduction of fatalities is immediately possible by installing properly designed roll-over protective structure (ROPS) and seat belts on loaders.

2. Most front-end loader fatal accidents occur as the result of the operator error produced by haste, carelessness, or lack of training or by any combination of all three of these factors, particularly while operating in reverse and while traveling downgrade.

3. Reduction of fatalities can be achieved by providing adequate training for any employee who might be expected to operate a loader in any capacity.

4. The accident reports often cite the lack of berms on roadways and stockpiles. The safety values provided by extensive use of high berms should be stressed to mine operators.

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Application of Statistics to Radiation Surveys in Mines

UNITED STATES DEPARTMENT OF THE INTERIOR
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Washington, D. C. 20240

U.S. Mining Enforcement & Safety Administration

Informational Report 1020

Application of Statistics to Radiation Surveys in Mines

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UNITED STATES DEPARTMENT OF THE INTERIOR
Stanley K. Hathaway, Secretary

Mining Enforcement and Safety Administration

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APPLICATION OF STATISTICS TO RADIATION SURVEYS IN MINES

by

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ABSTRACT

This Mining Enforcement and Safety Administration publication emphasizes the practical application and importance of counting statistics in analyzing radiation samples from radiation surveys of mines; it explains the random nature of measurements, illustrates statistical treatment of data; and shows the need for planning of sampling procedures on the basis of statistical criteria. The primary purpose of this publication is to familiarize mine inspectors and safety engineers with the seemingly complex subject of radiation data evaluation in terms of both practical and statistical accuracy through an extensive use of examples and sample problems.

INTRODUCTION

Radiation surveys constitute an important part of the work of mine safety engineers, health specialists, and inspectors in their efforts to assure the existence of healthy mine environment for employees. Exposure to alpha radiation stemming from radon daughters is not limited to uranium mine workers; many metal and nonmetal underground mines have also been found to contain hazardous concentrations of either radon gas and/or thoron gas and their progenies. In view of the random nature of radioactivity, some samples taken simultaneously show discrepancies in indicated radiation levels which can only be explained with the help of applied statistical methods, generally known as counting statistics.

Although most textbooks on health physics include a section on counting statistics, published information does not specifically deal with the problems which must be faced by mine health and safety personnel.

In regard to radiation sample accuracy as related to counting statistics, this publication is designed to discuss the various aspects of applied statistics relevant to mine radiation measurements, including natural fluctuations in physical properties of sources of radiation encountered in mines.

[1]Mining engineer, Radiation Group.

The experience of many radiation surveys and the data accumulated by the Denver Technical Support Center was used in numerous examples cited in this publication. The definitions of some basic statistical terms are given in the text, but no attempt was made to show mathematical derivation of the formulas used. Readers interested in the theory of statistics and its application in health physics are referred to the partial list of related books in the appendix.

ERRORS IN MEASUREMENTS OF PHYSICAL PROPERTIES

Radiation surveys of underground mines include measurements of radon daughters in mine air, radon and thoron content of mine atmosphere, gamma radiation in mine workings, radon and radium content of mine waters, and other physical parameters such as air velocity, small-particle concentrations in mine air, etc. Radioactive samples counted repeatedly within a short period of time exhibit variations which cannot be explained solely by laws of radioactive decay and ingrowth of progeny. The difficulty in obtaining consistent readings is obvious when using rate meters for radiation measurements: Here, the needle fluctuates between two values on the dial, and the operator must make a visual and mental averaging of two values within a short period of time, say 15 seconds. Digital scalers eliminate the guesswork and some of the human mistakes associated with rate meter readings, but the basic problems of all physical measurements remain unsolved, and the following statements are always true: (a) <u>no measurement is exact</u>, (b) <u>every measurement contains errors</u>, (c) <u>the true value of a measurement is never known</u>, and therefore (d) <u>the exact error present is always unknown</u>.

Classification of Errors

In radiation surveys the scattering of experimental data can be partly explained by the existence of a variety of errors. The nature of errors can be recognized and their individual contribution to the total error can be estimated. There are three basic kinds of errors:

(1) blunders

(2) systematic (instrumental) errors

(3) random (statistical) errors

A different classification of errors, used in evaluation of radiation-counting systems, includes two groups: reproducibility errors and inherent errors.

Blunders

Blunders are large personal errors which cannot be blamed on procedures prescribed for measurements. Blunders are due to human error or a sudden change in operating conditions of the equipment; they are suspected when the data from a series of measurements include values inconsistent with the otherwise homogeneous nature of the subject of investigation. Blunders include the slip of the pen, omission, and transposition of digits in recording the data.

Jarring or shaking of the equipment, faulty electrical contacts, improper setting of high voltage, etc., will produce obvious discrepancies in the data. Suspect data should be discarded only in cases where the relationship with blunders is clearly established. Scattering of values is not a sufficient reason for rejecting unusual data in a series of measurements. Statistical approach, described later in this publication, concerns the considerations necessary for judging what data should be treated as inconsistent.

Systematic (Instrumental) Errors

Systematic errors either remain constant throughout a series of measurements, or change temporarily following some physical law. This kind of error results from malfunction of equipment, nonlinearity of meter response, inconsistency of geometry (relative position of sample and detector), self-absorption, incorrect zero setting, unaccounted changes in background counts, or improper calibration of instrument.

Another category of systematic errors is produced by the counting equipment. Each detector in combination with its scaler has a finite resolution time ("dead time") during which some events of radioactive decay go undetected. These unregistered counts contribute to the total statistical errors of the system.

Random (Statistical) Errors

Repeated measurements performed on the same radioactive sample produce different values even though all conditions remain the same. Radioactivity is a spontaneous decay of atomic nuclei and subject to the laws of statistics. Had we the ability to isolate a single radioactive atom and to observe it until it decayed, there would be no way to predict the exact time for its disintegration. Considering a large number of radioactive atoms, some will decay promptly, while others may wait many years for the proper degree of unstable conditions to occur inside the nucleus. Every nucleus of a given species has an equal chance of decaying in a given time interval. For a large number of atoms of the same species, it is possible to predict how many atoms will decay within a certain period of time. Each disintegration is an independent event, which has no effect on the eventual decay of any other nucleus in the sample. The chance for decaying does not vary with age; an old nucleus has the same probability for decay that it had when it was first formed. The larger the number of atoms, the more accurate will be the prediction of the number of disintegrations over a given time period.

Due to the random nature of radioactivity, the resulting random errors of counting cannot be prevented; they can be accounted for by application of the methods of statistical analysis.

Reproducibility Errors

The errors of reproducibility are determined by repeated counting of the sample following the same procedures. The resulting data will show a scattering of values about the mean value as illustrated in figure 1. The range of

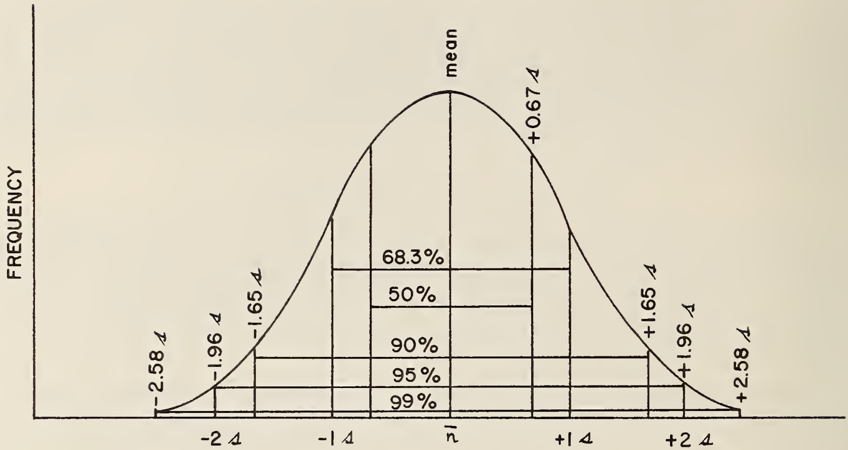

FIGURE 1. - Frequency of errors, standard deviation s, and confidence levels for a large number of measurements (over 30).

scattering will depend upon many factors, many of which are accidental in nature. An evaluation of errors in reproducibility will determine the sensitivity and precision of the method.

Inherent Errors

Inherent, or "built-in," errors result from unforeseen factors inherent to the nature of physical properties upon which the method of measurement is based. These errors cannot be exposed by repeated sample measurements when the same procedures are followed. To expose the inherent error, a set of samples should be analyzed by another known reliable method and the results compared with the data obtained by the method under investigation. As an alternative, a number of standard sources of precisely known activity can be used to verify the presence of inherent method errors.

Precision and accuracy can be defined in terms of reproducibility and inherent errors. A homogeneous sample measured repeatedly under similarly controlled conditions will produce a number of values which may or may not differ widely from the true value even though systematic errors are present throughout the measurements. The degree of reproducibility is known as precision of the method; it is expressed by the standard deviation s, which is a measure of deviation of individual measurements from the sample mean (see "Standard Deviation" below). Accuracy refers to the agreement between the true activity of the sample and the value obtained by the method used. Symbol σ will be used to denote the standard deviation of measurements from the true value, and symbol s will represent the standard deviation of experimental values.

Relative error, or accuracy, is deviation of the mean of measurements from the true value as a percentage of the true value. Standard sources can be used to determine both, precision and accuracy of the method. On the other hand, any homogeneous sample can be used to determine the precision alone. A method may have a very high precision (good reproducibility) but measure only a part of the sample activity; on the other hand, a measurement although highly precise, may be in error because of improperly calibrated equipment (poor accuracy). A low instrument sensitivity may cause very low precision even though the method is very accurate.

APPLICATION OF COUNTING STATISTICS TO RADIATION SURVEYS IN MINES

Arithmetic Mean

Random processes are subject to the law of probability and one of the basic assumptions of this law is that the best estimate of the true value of a group of repeating measurements is the arithmetic mean. The mean itself is subject to error.

Example 1. Count Rate of a Check Source

Standard radioactive sources, made of relatively long-lived isotopes to produce "constant" counts, are usually applied for on-the-spot performance checks of counting equipment. Ten 3-minute counts were taken using a Th-230 performance standard with the following results indicating the random nature of radioactivity:

4,513	4,530
4,643	4,514
4,661	4,578
4,583	4,582
4,507	4,501

What is the best estimate of the true 3-minute count for this Th-230 source?

Solution

Arithmetic mean is the best estimate of the true count in repeating measurements. It is computed by summing the above values and dividing the sum by the total number of observations.

The sum of all counts	45,612 counts
Number of observations	10
Arithmetic mean	45,612÷10=4,561 counts

Standard Deviation

Although radioactivity-counting methods include errors and the true value of a measurement can never be known due to instrumental limitations, statistical methods make it possible to narrow the range of values toward the true value.

Standard deviation is the most-used measure of interpreting and evaluating the range of errors in a single or repetitive measurement of a quantity. The word "standard" in the term standard deviation does not have a particular meaning; it is merely a name to distinguish this measure of deviation from many others which are not discussed in this publication. The term standard deviation does not imply that other kinds of deviations are unusual. The formula for calculation of experimental standard deviation of a single measurement is·

$$s = \pm \sqrt{\frac{\Sigma(n_i - \overline{n})^2}{m-1}} = \pm \sqrt{\frac{\Sigma d^2}{m-1}}, \tag{1}$$

where n_i = measurements taken repeatedly under similar conditions,

$\overline{n}$ = arithmetic mean of the data,

m = number of measurements (samples),

d = $(n_i - \overline{n})$ deviations from the mean,

and d^2 = mean square.

The $\pm$ sign in front of standard deviation indicates the statistical (random) nature of this error.

Example 2. Standard Deviation of Repeated Measurements

Assuming that the data shown in example 1 do not include systematic errors, compute the standard deviation for the series of measurements listed in example 1.

Solution

The original 10 counts of the check source are entered in the first column of table 1. The average value of all counts was $\overline{n}$ = 4,561 (see example 1). Each count n_i of the first column of table 1 is compared with $\overline{n}$ and the difference is shown in the second column, including its algebraic sign. The third column consists of the squared values of the second column; it is known as the mean square.

TABLE 1. - Computing experimental standard deviation

Check-source counts, n_1	Deviations from mean $d=(n_1-\bar{n})$	Mean square $d^2=(n_1-\bar{n})^2$
4,513	-48	2,304
4,643	82	6,724
4,661	100	10,000
4,583	22	484
4,507	-54	2,916
4,530	-31	961
4,514	-47	2,209
4,578	17	289
4,582	21	441
4,501	-60	3,600
Mean...$\bar{n}$=4,561	-	Total...Σ=29,928

$$\text{Standard deviation } s = \pm\sqrt{\frac{\Sigma d^2}{m-1}} = \pm\sqrt{\frac{29{,}928}{10-1}} = \pm 57 \text{ counts}$$

Conclusions

a. The best estimate of the count of the check source is 4,561 counts.

b. Standard deviation of a single measurement is 57 counts.

c. Seven out of ten values fall within the range of 4,561±57; that is, they range between 4,504 and 4,618 counts.

The last conclusion is a part of the definition of the standard deviation. A further discussion of probabilities in the following pages will clarify this point.

The variations in repeated short-period measurements of a long-lived isotope, such as Th-230, were used here to illustrate the technique of standard deviation calculation. In practice, one reading, that is long enough to meet statistical requirements, is used to check the instrument performance; the standard deviation of the single observation is then calculated as explained in the following pages.

Error of the Mean

The arithmetic mean, computed from the data which contain errors, is also subject to error. When a measurement is repeated, the statistical errors tend to balance out and the remaining errors of the series of measurements are proportional to the square root of the number of observations. This means that to reduce the error by one-half, four times as many measurements must be taken. Experimental standard deviation of the mean is determined by the following formula:

$$s_{\bar{n}} = \pm\frac{s}{\sqrt{m}} = \pm\sqrt{\frac{\Sigma d^2}{m(m-1)}}\ . \qquad (2)$$

The symbols in this formula are the same as in formula 1.

Example 3. Computing the Error of the Mean

Using the data of examples 1 and 2, calculate the standard deviation of the mean.

Solution

$$s_{\bar{n}} = \pm \frac{s}{\sqrt{m}} = \pm \frac{57}{\sqrt{10}} = \pm 18 \text{ counts.}$$

This means that the true value of the mean has 7 out of 10 chances for having a value within the range of 4,561±18, or 4,543 to 4,579 counts.

Error of a Single Observation

Experimental standard deviation of a single measurement is equal to the square root of that measurement:

$$s_1 = \pm \sqrt{n}\,. \tag{3}$$

Here n = total number of counts obtained in measurement.

Example 4. True Value on the Basis of Single Measurement

Using properly calibrated equipment, the mine air was sampled for radon daughters by passing a known volume of air through the filter; the subsequent counting of the filter produced 375 counts per 5 minutes. What is the range of values where the above count has a good chance of occurrence?

Solution

$$s_1 = \pm \sqrt{375} = \pm 19.4 \simeq \pm 19 \text{ counts.}$$

There are 7 out of 10 chances that the true sample count lies between 375±19, or 356 and 394 counts.

Standard Deviation of Count-Rate Meter

A count-rate meter produces a weighted average count rate, with the most recent count being given the most weight. The standard deviation of the count rate can be calculated when the integrating circuit capacitance and resistance are known:

$$s_{crm} = \sqrt{\frac{r}{2RC}}\,, \tag{4}$$

where s_{crm} = standard deviation of count-rate meter,

r = sample count rate,

R = resistance (ohms),

and C = capacitance (farads).

The term RC is known as the integrating time constant, or the effective collection time of the instrument.

Propagation of Errors

Sometimes several independent measurements are combined to produce a single result. Each measurement is subject to errors and the end result contains a combination of errors. For instance, when a sample of airborne radioactivity is taken on a filter using a pump, and consequently counted, the following random errors affect the obtained count:

s_1 = random error of pump calibration; it is part of airflow calculation,

s_2 = random error of timing; accuracy of the stopwatch,

s_3 = random error of scaler calibration,

s_4 = random error of timer used in conjunction with scaler.

The errors of timing devices (stopwatch, timer) are important when high-volume pumps are used and/or high count rates are observed.

The following formula illustrates the concept of error propagation:

$$s_{\Sigma} = \sqrt{s_1^2 + s_2^2 + \ldots + s_n^2}\,, \tag{5}$$

where s_{Σ} reflects the total statistical error caused by random errors $s_1, s_2, \ldots, s_n$ of various origin.

Data Variations Due to Fluctuations in Concentration of Radioactivity in the Rocks

Samples of apparently homogeneous natural substances such as rocks, ground water, and air differ from their own kind not only due to the errors of measurements, but also because they are natural objects and are expected to exhibit chance variations in their properties. Statistical treatment of the data will evaluate the reliability of the methods used and determine the variations of natural properties involved.

Measurements of radioactivity in the rocks include total statistical errors of the methods involved. To estimate the range of natural concentration, the concept of error propagation is used. The inherent error σ is determined by comparison with an independent accurate method. According to formula 5:

$$s = \sqrt{s_{nat}^2 + \sigma^2}\,, \tag{5a}$$

where s = total standard deviation of measurements,

s_{nat} = standard deviation reflecting fluctuations in concentration of radioactivity in samples,

σ = inherent error, determined by independent accurate method.

Rearranging formula 5a gives:

$$s_{nat} = \sqrt{s^2 - \sigma^2}.$$

Similarly, the error of the mean, which is due to fluctuations of radioactivity alone, is computed when the inherent error is known:

$$s_{\bar{n}\ nat} = \sqrt{\frac{s_n^2 - \sigma^2}{m}}, \tag{6}$$

where $s_{\bar{n}}$ = total error of the mean,

and m = number of samples used.

Rejecting Unusual Data

Repeated measurements of samples may produce radiological data containing some unusually high or low values which may result from blunders. When the total number of measurements exceeds 200, a simple rule of thumb may be used for recognizing and rejecting unusual data: Values differing from the mean by three to four standard deviations should be rejected and the standard deviation of remaining data recalculated. In cases where such rejections are numerous, the source of blunders should be determined.

When the number of measurements is less than 200, the Chauvenet's criterion is used for rejecting the unusual data. First, the value of $\frac{|n-\bar{n}|}{s}$ is calculated. Here n is the suspected count, $\bar{n}$ is the average of all counts, and s is the standard deviation. The absolute value of experimental ratio $\frac{n-\bar{n}}{s}$ is not to exceed its theoretical value given in table 2 for the same number of measurements. The following example explains the procedure.

TABLE 2. - Chauvenet's criterion for rejection of data

Number of measurements	Theoretical value of $\lvert n-\bar{n}\rvert \div s$	Number of measurements	Theoretical value of $\lvert n-n\rvert \div s$
2	1.15	15	2.13
3	1.38	20	2.24
4	1.54	25	2.33
5	1.65	30	2.40
6	1.73	35	2.45
7	1.80	40	2.50
8	1.86	50	2.58
9	1.91	75	2.71
10	1.96	100	2.81
12	2.04	200	3.02

Example 5. Recognizing and Rejecting Unusual Data

The following counts were obtained in the process of equipment calibration:

550	652
970	693
650	645
663	650
671	

The two first values are suspect: 550 is low and 970 is too high in comparison with the rest of the counts. Using Chauvenet's criterion, determine if these counts should be considered unusual and excluded from calculations.

Solution

Using the method shown in table 1, we compute the mean and the standard deviation of all nine values with the following results:

$\bar{n}$ = 683 counts,

s = 115 counts.

First we test the validity of 550 counts:

$$\frac{\lvert n-\bar{n}\rvert}{s} = \frac{\lvert 550-683\rvert}{115} = 1.16.$$

Reference to table 2 shows that for nine measurements the value in the second column is 1.91. Obviously 550 counts meet the requirement: Experimental value of $\lvert n-\bar{n}\rvert \div s$ does not exceed its theoretical (probable) value, and

cannot be rejected at this point. On the other hand, $|970-683| \div 115 = 2.49$ and is in excess of 1.91. Thus, 970 counts should be rejected. The renewed calculation of the mean and standard deviation gives $\bar{n}=647$ and $s=42$. Application of Chauvenet's criterion to 550 counts at this point produces a different result: $|550-647| \div 42 = 2.30$. Since the probable value in the second column of table 2 is 1.86 for eight measurements, the 550 counts are rejected, and the new set of data, now reduced to seven values, has a mean of $\bar{n}=661$ and a standard deviation of $s=17$ counts. At this point, the 693 counts happen to be at the verge of rejection because $|693-661| \div 17 = 1.90$, and 1.90 is slightly in excess of acceptable value of 1.80 in table 2. This example points to the possibility of blunders in the above calibration.

Data Reliability--Confidence Levels--Probability

On the basis of a number of measurements we can determine $\bar{n}$, the arithmetic mean, and s, the standard deviation which will give the range of values within which the true value has a good chance of occurring. Before attempting to compare similar data obtained at different locations or times, we must make sure that the data have the same degree of reliability. Such reliability is expressed in terms of probability, or confidence levels. When the range of values is such that the true value has 9 out of 10 chances to fall within this range, we deal with a 90-percent confidence level. The most commonly used confidence level in counting radioactivity is 95 percent; in other words, we allow only 5 percent probability that the true value of the mean may be outside of the range of values.

Standard deviation is a measure of data scattering around the mean and can be used for setting various confidence levels for given data. Thus, one standard deviation determined from a large number of measurements (30 or more) will provide 68 percent confidence. Two standard deviations for the same set of data provides 96 percent confidence that the true mean will fall within the range of $\bar{n} \pm 2s$. Table 3 lists confidence levels and corresponding numbers of standard deviations for setting the range of data scattering. The obvious disproportion between confidence levels and the number of standard deviations in table 3 is due to the fact that their relation is not linear. The errors are scattered around the mean $\bar{n}$ following a bell-shaped curve and confidence levels represent the area under specific sections of the curve (fig. 1).

TABLE 3. - Confidence levels and number of standard deviations for large number of measurements (over 30)

Confidence level, percent	Number of standard deviations, K	Confidence level, percent	Number of standard deviations, K
50	0.68	95	1.96
68	1.0	96	2.0
90	1.64	99	2.57

Example 6. Range of Values at 95 Percent Confidence Level

A large number of observations produced an average of 1,275±74 counts. What is the range of counts at the 95-percent confidence level?

Solution

The range of values reported above is at 68 percent confidence level (one standard deviation). The general formula for reporting the range of values is $\bar{n} \pm Ks$. Here $\bar{n}=1,275$, $s=74$, and $K=1.96$ for 95 percent confidence level (table 3).

$$1,275 \pm 1.96 \times 74 = 1,275 \pm 145 \text{ counts.}$$

Computing Confidence Levels for a Limited Number of Measurements

When the number of measurements is less than 30, the curve of figure 1 departs from the ideally smooth bell-shaped curve of normal distribution; one standard deviation will no longer represent 68 percent confidence level, and coefficients larger than K of table 3 must be applied to make up for the uncertainties due to the small number of measurements.

Most radiation-measuring methods of underground surveys employ a limited number of measurements. It becomes necessary to apply the Student-t coefficient in setting the range for the mean value at a given confidence level. Table 4 lists Student-t coefficients for given confidence levels at various "degrees of freedom." The number of degrees of freedom equals the number of measurements minus one: d.f. = m-1.

The following formula is used for computing the range of values for a limited (less than 30) number of measurements:

$$\text{range of values} = n \pm t \cdot s_{\bar{n}}, \tag{7}$$

where t = Student coefficient (table 4),

and $s_{\bar{n}}$ = standard error of the mean.

TABLE 4. - Student-t coefficients for various confidence levels and degrees of freedom (d.f.)

	Student-t coefficients		
Confidence levels, percent.....	68	95	99
Degrees of freedom, d.f. = m-1:			
1	2.0	12.7	63.7
2	1.3	4.3	9.9
3	1.3	3.2	5.8
4	1.2	2.8	4.6
5	1.2	2.6	4.0
6	1.1	2.4	3.7
7	1.1	2.4	3.5
8	1.1	2.3	3.4
9	1.1	2.3	3.3
10	1.1	2.2	3.2
11	1.1	2.2	3.1
12	1.1	2.2	3.1
13	1.1	2.2	3.0
14	1.1	2.1	3.0
15	1.1	2.1	2.9
20	1.1	2.1	2.8
30	1.1	2.0	2.7
40	1.1	2.0	2.7
60	1.0	2.0	2.7
∞	1.0	2.0	2.6

Example 7. Computing the Range of Values at Given Confidence Level on Basis of Limited Number of Measurements

The check source of example 1 indicated an average of 4,561±57 counts as a result of 10 measurements. The error of the mean, according to formula 2, is $\frac{57}{\sqrt{10}}$ = 18 counts (see example 3). What is the range of values within which the true count of check source will occur at 95 percent confidence level?

Solution

Student-t coefficient for 9 degrees of freedom at 95 percent confidence level is 2.3 (table 4):

$$\overline{n} \pm t \cdot s_{\overline{n}} = 4{,}561 \pm 2.3 \times 18 = 4{,}561 \pm 41 \text{ counts.}$$

Comparison Between Means--Test of Significance

When using a new type of equipment or a different method, the same set of values is measured by two or more sets of equipment or methods. Similarly, a natural property may be measured at two different locations of the mine by using the same equipment and applying the same procedure; when two means are considerably different, we can intuitively form an opinion regarding the accuracy of instruments and methods, or decide whether there is a difference

between the values at two locations. On the other hand, if the differences between the means are small, no amount of intuition will help: Is the difference between the means due to the random nature of radioactivity, or does it reflect a true difference between observed values? Only a statistical analysis can provide the answer within a specified level of confidence.

The following formulas are used to compute the experimental value of t_{exp}. This, then, is compared with theoretical value of Student-t coefficient (table 4) at the desired level of confidence. If t_{exp} exceeds the table 4 value, the difference between the means is significant, that is, there is a true difference; otherwise, the apparent difference is due to chance.

$$t_{exp} = \frac{\bar{n}_1 - \bar{n}_2}{S} \sqrt{\frac{m_1 \cdot m_2}{m_1 + m_2}}\,, \tag{8}$$

$$S = \sqrt{\frac{s_1^{\,2} + s_2^{\,2}}{m_1 + m_2 - 2}}\,, \tag{9}$$

$$\text{d.f.} = m_1 + m_2 - 2\,. \tag{10}$$

where $\bar{n}_1$ and $\bar{n}_2$ = means of two sets of data,

S = mean square of standard deviations,

and m_1 and m_2 = number of measurements in each set.

Example 8. Comparison Between the Readings of Inspector and the Company

Two sets of air samples were taken at the same time and place, one by a mine inspector, another by the company's ventilation engineer. Both men followed the same procedure of sampling, counting, and working level calculation, with the following results·

Inspector's sampling	Company's sampling
n_1 = 0.315 WL	n_1 = 0.305 WL
n_2 = 0.305 WL	n_2 = 0.285 WL
n_3 = 0.295 WL	n_3 = 0.295 WL
$\bar{n}$ = 0.305 WL	$\bar{n}$ = 0.295 WL
s = 0.01 WL	s = 0.01 WL

The inspector's sampling produced a mean of 0.305 WL indicating a radiation level slightly in excess of 0.3 WL; the company's sampling indicated a marginal situation, but acceptable radiation level, 0.005 WL below 0.3 WL.

Question

Are the above assumptions accurate? Is the total difference of 0.01 WL due to the random nature of counting, or does it reflect a significant difference and calls for recalibration of one or both instrument systems?

Solution

Student-t test of significance is carried out in the following manner:

$$S = \sqrt{\frac{(0.01)^2 + (0.01)^2}{3 + 3 - 2}} = 0.007,$$

$$t_{exp} = \frac{0.305 - 0.295}{0.007}\sqrt{\frac{3 \times 3}{3+3}} = 1.7,$$

d.f. = 3+3-2 = 4 degrees of freedom.

Theoretical value of t at 95 percent level of confidence and 4 degrees of freedom (table 4) is 2.8. Thus, t_{exp} does not exceed theoretical t, and the difference between two means can be attributed merely to the randomness of measured values. The only valid conclusion which can be made from the data is that the samples are in agreement within statistical expectations.

Example 9. Effect of Larger Number of Samples in Case of Dispute

Given the data of example 8, the mine inspector and the company engineer could decide to clarify the situation by increasing the number of concurrent samples to five each. Let us suppose that the means and their standard deviations remained the same. Now:

$$S = \sqrt{\frac{(0.01)^2 + (0.01)^2}{5 + 5 - 2}} = 0.005$$

$$t_{exp} = \frac{0.305-0.295}{0.005}\sqrt{\frac{5 \times 5}{5+5}} = 3.2.$$

At 5+5-2=8 degrees of freedom and 95 percent confidence level the theoretical value of t is 2.3 (table 4). Thus, the experimental value of t_{exp} = 3.2 exceeds the theoretical Student-t value, the difference between two means is significant; in other words, the data are not within statistical expectations, and one or both sets of sampling instruments need recalibration.

Example 10. Difference in Radon Content at Two Points of a Drift

Paired measurements of radon content of air were taken at two stations along a mineralized drift in an experiment designed to determine the rate of radon release by the exposed rock. Here is the data:

$m_1 = m_2 = 14$ = number of concurrent measurements,

$\overline{n}_1 = 822$ pCi/l mean value at downstream station,

$\overline{n}_2 = 797$ pCi/l mean value at upstream station,

$s_1 = 136$ pCi/l standard deviation of downstream values,

$s_2 = 157$ pCi/l standard deviation of upstream values.

<u>Question</u>

Is the difference between two means significant? In other words, is it necessarily due to the radon being released by the exposed rock between two stations? If the answer is no, then the difference between means can possibly be attributed to the chance variation in counting.

<u>Solution</u>

$$S = \sqrt{\frac{(136)^2 + (157)^2}{14 + 14 - 2}} = 41,$$

$$t_{exp} = \frac{822-797}{41}\sqrt{\frac{14 \times 14}{14+14}} = 1.6,$$

d.f. = 14+14-2=26 degrees of freedom.

Theoretical value of Student-t for 26 degrees of freedom at 95 percent confidence level is between 2.0 and 2.1 (table 4). Thus, experimental value $t_{exp} = 1.6$ does not exceed the theoretical value of t and therefore the difference of 25 pCi/l between two means does not have a statistical significance. Conclusion: The amount of radon, if any, released between the two stations cannot be substantiated statistically from the acquired data.

<u>Random Behavior of Radioactivity-Counting Systems</u>

Due to the random nature of radioactivity, counting systems are <u>expected</u> to produce diverse data within acceptable limits. The data produced by counters must be random in distribution if the counter is performing reliably. The statistical nature of data is determined by chi square (χ^2) test. The following formula is used in calculation of experimental value of chi square,

which is then compared with theoretical value of χ^2 given in table 5.

$$\chi^2_{exp} = \frac{\Sigma\ (n_i - \bar{n})^2}{\bar{n}} . \tag{11}$$

Here the symbols are the same as in formula 1 for standard deviation.

TABLE 5. - Theoretical values of chi square

Probabilities, percent........	1	5	10	50	90	95	99
Degrees of freedom (m-1):							
1........................	6.6	3.8	2.7	0.4	0.01	0.00	0.00
2........................	9.2	5.9	4.6	1.4	0.2	0.10	0.02
3........................	11.3	7.8	6.2	2.4	0.6	0.35	0.11
4........................	13.3	9.5	7.8	3.4	1.1	0.71	0.30
5........................	15.1	11.1	9.2	4.3	1.6	1.14	0.55
6........................	16.8	12.6	10.6	5.3	2.2	1.63	0.87
7........................	18.5	14.1	12.0	6.3	2.8	2.17	1.24
8........................	20.1	15.5	13.4	7.3	3.5	2.73	1.65
9........................	21.7	16.9	14.7	8.3	4.2	3.32	2.09
10.......................	23.2	18.3	15.9	9.3	4.9	3.94	2.56
11.......................	24.7	19.7	17.3	10.3	5.6	4.57	3.05
12.......................	26.2	21.0	18.5	11.3	6.3	5.22	3.57
13.......................	27.7	22.4	19.8	12.3	7.0	5.89	4.11
14.......................	29.1	23.7	21.1	13.3	7.8	6.57	4.66
15.......................	30.6	24.9	22.3	14.3	8.5	7.26	5.23
16.......................	31.9	26.3	23.5	15.3	9.3	7.96	5.81
17.......................	33.4	27.6	24.8	16.3	10.1	8.67	6.41
18.......................	34.8	28.9	25.9	17.3	10.9	9.39	7.01
19.......................	36.2	30.1	27.2	18.3	11.6	10.12	7.63
20.......................	37.6	31.4	28.4	19.3	12.4	10.85	8.26
21.......................	38.9	32.7	29.6	20.3	13.2	11.59	8.90
22.......................	40.3	33.9	30.8	21.3	14.0	12.34	9.54
23.......................	41.6	35.2	32.0	22.3	14.8	13.09	10.19
24.......................	42.9	36.4	33.2	23.3	15.7	13.85	10.86
25.......................	44.3	37.6	34.4	24.3	16.5	14.61	11.52
26.......................	45.6	38.9	35.6	25.3	17.3	15.38	12.20
27.......................	46.9	40.1	36.7	26.3	18.1	16.15	12.88
28.......................	48.3	41.3	37.9	27.3	18.9	16.93	13.56
29.......................	49.6	42.5	39.1	28.3	19.8	17.70	14.26
30.......................	50.9	43.8	40.2	29.3	20.6	18.49	14.95
40.......................	63.7	55.8	51.8	39.3	29.0	26.51	22.16
60.......................	88.4	79.1	74.4	59.3	46.5	43.19	37.48
100......................	135.8	124.3	118.5	99.3	82.4	77.93	70.06

Table 5 lists theoretical values of chi square for various degrees of freedom and various probabilities. The number of degrees of freedom is merely one less than the number of measurements, that is m-1. The experimental χ^2 value calculated by formula 11 must have a reasonable probability of occurrence shown in table 5, to signify a reliable performance. Two extreme probabilities of table 5, that is, less than 1 percent and more than 99 percent,

are not acceptable. Figure 2 is a graphical illustration of chi square values and can be used for chi square tests.

Example 11. Testing Counter Reliability by Chi Square Method

Using the data of example 1, check the counter performance by chi square test.

Solution

According to table 1:

$$\Sigma\ (n_i - \bar{n})^2 = 29,928$$

$$\bar{n} = 4,561.$$

Therefore $$\chi^2_{exp} = \frac{\Sigma\ (n_i - \bar{n})^2}{\bar{n}} = \frac{29,928}{4,561} = 6.6.$$

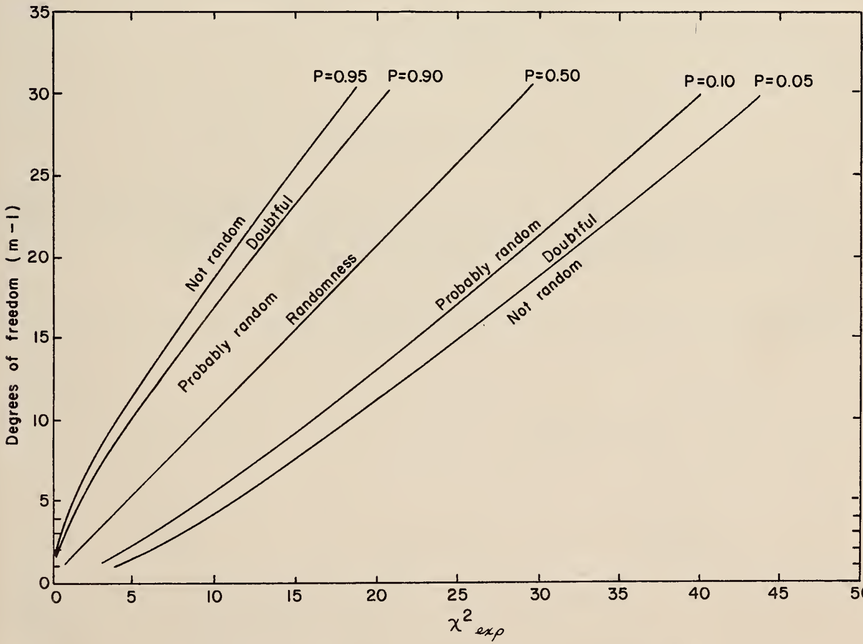

FIGURE 2. - Graphical illustration of chi square values.

Reference to table 5 indicates that at 10-1=9 degrees of freedom the value of χ^2_{exp} = 6.6 falls between 4.2 (90 percent probability) and 8.3 (50 percent probability). This indicates a proper and reliable operation of the counter from a statistical viewpoint. Reference to figure 2 produces a similar conclusion

PLANNING OF RADIOACTIVITY-COUNTING PROCEDURES

Sample Size

A sample should be large enough to assure the desired accuracy. The following formula and example illustrate the sample-size computation:

$$N = \left(\frac{K \cdot s}{E \cdot \bar{n}} \right)^2, \tag{12}$$

where N = sample size,

K = factor taken from table 3,

s = standard deviation,

E = error of average concentration,

and $\bar{n}$ = average concentration.

Example 12. Size of Air Sample in Survey of Radon Concentration

A preliminary sampling of mine atmosphere indicated a radon concentration of 797 pCi/1 with a standard deviation of 157 pCi/1 (example 10). What volume of air must be pumped to assure that the error will be not more than 5 percent of the average concentration at 95 percent confidence level?

Solution

K = 1.96 (table 3),

s = 157 pCi/1,

E = 0.05 acceptable error,

$\bar{n}$ = 797 pCi/1.

$$N = \left(\frac{1.96 \times 157}{0.05 \times 797} \right)^2 = 59\ 6 \simeq 60 \text{ liters.}$$

Example 13. Error Introduced Due to Small Sample

Let us suppose that routine air sampling has been done at a rate of 10 l/min for 5 min, that is, 50 instead of the required 60 liters of air were sampled in the example above. What is the resulting error?

In formula 12 the unknown is E.

$$50 = \left(\frac{1.96 \times 157}{E \times 797}\right)^2,$$

$$E = \frac{1.96 \times 157}{\sqrt{50} \times 797} = 0.055 = 5.5 \text{ percent error.}$$

In comparison with example 12, taking a smaller sample will result in 0.5 percent additional error.

Number of Counts Required

To achieve a required accuracy at a given confidence level it is necessary to reach a certain total count for the sample.

$$N = \left(\frac{K}{E}\right)^2, \tag{13}$$

where N = total counts required,

K = factor from table 3,

and E = acceptable error.

Example 14. Total Count Required for Given Accuracy at Certain Confidence Level

What is the total number of counts needed for a 95-percent probability that the error of the count will not exceed 10 percent?

Solution

K = 1.96 (table 3),

E = 0.10,

$$N = \left(\frac{1.96}{0.10}\right)^2 = 384 \text{ counts.}$$

Thus, a sample representing low ranges of radiation but approaching regulatory values (0.3 WL, for example) should be counted long enough to satisfy the minimum total count specified above.

Effect of Background on Total Count

In most cases background radiation contributes to the total count of the sample. The errors affecting the accuracy of sample counting will also affect the background counts; thus, when the background count is subtracted from the gross sample count, the resulting net count is subject to combined error.

Standard deviation of the net sample count is given by the following formula:

$$s_s = \sqrt{s_t^2 + s_b^2} = \sqrt{N_t + N_b} \tag{14}$$

where s_t = standard deviation of total sample count,

s_b = standard deviation of background count,

N_t = total count,

and N_b = background count.

Example 15. Required Total Count in Presence of Background

Two stations are selected along a mineralized drift for bulk radon emanation measurements. Radon content of the downstream station exceeds the radon concentration of upstream station by 4 percent. How many counts are necessary for a 95-percent probability that the error of the sample count shall be no more than 10 percent?

Solution

The 4-percent increase in radon content at the downstream station is due to radon release from the exposed rock of the drift. Half-life of radon is 3.825 days, hence the radon content at the upstream station will not diminish significantly through radioactive decay while the radon gas is moving between the two stations. Therefore, the upstream reading can serve as background for the downstream measurement; formula 14 can be applied to the downstream station.

The acceptable error of this example is 10 percent of the net count, or $0.10\ (N_t - N_b)$. The 95-percent confidence level corresponds to 1.96 standard deviations (table 3); the acceptable error will be:

$$0.10(N_t - N_b) = 1.96\ s_s\ ,$$

or by using formula 14:

$$0.10(N_t - N_b) = 1.96\ \sqrt{N_t + N_b}\ ;$$

on the other hand, the net sample count

$$N_s = N_t - N_b\ .$$

In this example $N_s = 0.04N_b$

and $N_t = N_s + N_b = 0.04\ N_b + N_b = 1.04\ N_b$,

$$0.10\ (N_t - N_b) = 0.10\ (1.04N_b - N_b) = 0.10\ (0.04N_b) = 0.004\ N_b,$$

$$0.004\ N_b = 1.96\sqrt{N_t + N_b} = 1.96\sqrt{1.04N_b + N_b} = 1.96\sqrt{2.04N_b},$$

$$N_b = 2.04\ (1.96/0.004)^2.$$

N_b = 489,804 required counts at upstream station,

$N_s = 0.04\ N_b = 0.04 \times 489{,}804$ = 19,592 net count,

N_t = 489,804 + 19,592 = 509,396 total count,

or approximately 500,000 total counts are required to satisfy the accuracy at the downstream station.

Effect of Background on Total Error When Count Rates Are Used

Count rates, or counts obtained during a certain time, have been used previously to explain the errors of experimental counting. When background is present, its effect on counting error should be considered. The standard error of net counting rate of the sample is:

$$s_s = \sqrt{\frac{r_t}{t_t} + \frac{r_b}{t_b}}\ . \qquad (15)$$

where r_t = total counts per unit of time,

r_b = background counts per unit of time,

t_t = time spent on sample counting,

and t_b = time spent on background counting.

Example 16 Combined Errors of Sample and Background Counts

The air sample of example 4 produced a total of 375 counts during 5 minutes. A background count over 10 minutes indicated 18 counts. What percent error can be expected from the net sample count at 95 percent confidence level?

Solution

For 95 percent confidence level, formula 15, is:

$$1.96\ s_s = 1.96\sqrt{\frac{r_t}{t_t} + \frac{r_b}{t_b}}\ .$$

where $r_t = 375 \div 5 = 75$ counts/min, total rate,

$r_b = 18 \div 10 = 1.8$ counts/min, background rate,

$$1.96 \sqrt{\frac{75}{5} + \frac{1.8}{10}} = 7.6 \text{ counts/min, combined error,}$$

and $$\frac{7.6}{75} \times 100 = 10.2 \text{ percent, combined error.}$$

Distribution of Time Between Sample and Background Counting

To minimize the error of sample and background counting, the times assigned to these two operations can be optimized. This is an important consideration in planning of calibration procedure. The efficient distribution of counting time can be determined by the following formula:

$$\frac{t_t}{t_b} = \sqrt{\frac{r_t}{r_b}}, \tag{16}$$

where t and r stand for time and count rate, and subscripts t and b stand for total and background. Figure 3 is a graphical presentation of formula 16, designed to facilitate the computation as illustrated by the following example.

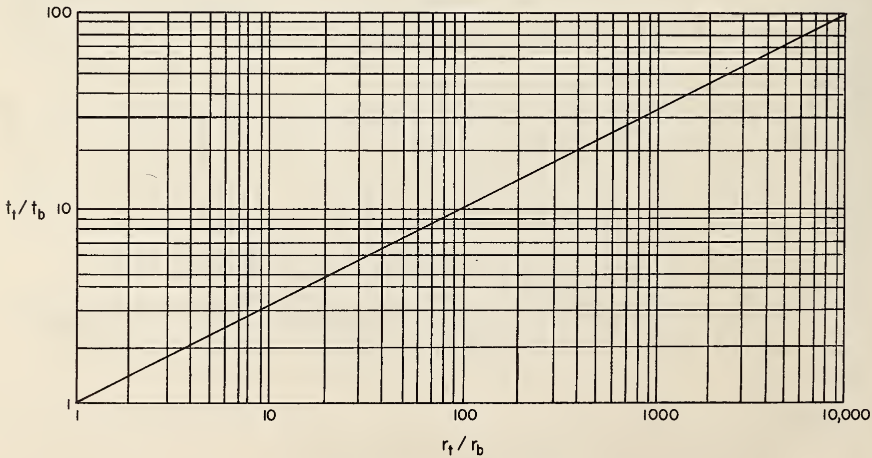

FIGURE 3. - Most efficient distribution of counting time.

Example 17. Efficient Distribution of Counting Time

In example 16, the sample (total) count rate is 75 and the background count rate is 1.8 counts/min. What is the best ratio between sample and background counting times?

Solution

$$\frac{r_t}{r_b} = \frac{75}{1.8} = 41.6 \simeq 42.$$

A reference to figure 3 shows that the value 42 on the horizontal scale corresponds to 6.5 on the vertical scale. This means that for the most efficient distribution of counting time with a minimum of counting error, the sample must be counted 6.5 times longer than the background.

CONCLUSIONS

Mining health and safety personnel should be able to qualify the results of radiation surveys and individual radon-daughter samples in terms of accuracy and reliability. Familiarity with the various kinds of errors encountered in physical measurements and an ability to use the techniques of applied statistics is necessary for theoretically sound data interpretation, data comparison, and identification of unusual values. Statistical considerations can also be used for the planning of efficient sampling and counting schedules in radiation surveys.

APPENDIX

Partial List of Books on Applied Statistics

1. Bar-Shalom, Y., D. Budenaers, R. Schainker, and A. Segall. Handbook of Statistical Tests for Evaluating Employee Exposure to Air Contaminants. HEW Publication No. 75-147 (NIOSH), U.S. Government Printing Office, Washington, D.C., 1975.

2. Brandt, Sigm. Statistical and Computational Methods in Data Analysis. American Elsevier Pub. Co., New York, 1970.

3. Cember, H. Introduction to Health Physics. Pergamon Press, Inc., Oxford, Great Britain, 1969, pp. 270-279.

4. Chase, G. D., and J. L. Rabinowitz. Principles of Radioisotope Methodology. Burgess Pub. Co., Minneapolis, Minn., 3d ed., 1967, pp. 75-107.

5. Gloyna, E. F., and J. O. Ledbetter. Principles of Radiological Health. Marcel Dekker, Inc., New York, 1969, pp. 123-137.

6. Lapp, R. E., and H. L. Anders. Nuclear Radiation Physics. Printice Hall, Inc., Englewood Cliffs, N.J., 4th ed., 1972, pp. 36-42.

7. Leidel, N. A., and K. A. Bush. Statistical Methods for the Determination of Noncompliance With Occupational Health Standards. TR-76, U.S. Department of Health, Education, and Welfare, PHS, NIOSH, Div. of Lab. and Criteria Development, Cincinnati, Ohio, 1974.

8. Li, J. C. R. Statistical Inference I--Revised Edition of Introduction to Statistical Inference--a Non-mathematical Exposition of the Theory of Statistics. Edwards Brothers, Inc., Ann Arbor, Mich., 1964, 658 pp.

9. Spiegel, M. R. Schaum's Outline Series--Theory and Problems of Statistics. McGraw-Hill Book Co., New York, 1961, 359 pp.

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